Possible enhancement to specifications of several Moderate Resolution Imaging Spectroradiometer visible and near-IR channels

Bo-Cai Gao,[a] Rong-Rong Li, [a] and Xiaoxiong Xiong[b]

[a] Remote Sensing Division, Code 7232, Naval Research Laboratory, Washington, DC 20375 USA
gao@nrl.navy.mil
[b] Code 614.4, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 USA
Xiaoxiong.Xiong-1@nasa.gov

Abstract. The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments onboard the NASA Terra and Aqua Spacecrafts have provided unprecedented capabilities in global observations of land, ocean, and atmosphere. In this paper, we report that, under certain atmospheric and surface conditions, several MODIS channels in the visible and near-IR spectral regions can saturate. The radiance dynamic ranges of similar channels for future satellite earth observing instruments should be increased. Instrument designers and MODIS data users should be aware of the saturation problems associated with these MODIS channels.

Keywords: remote sensing, MODIS, imaging, clouds, land, ocean color.

1 INTRODUCTION

Two Moderate Resolution Imaging Spectrometer (MODIS) instruments [1], [2], [3], one on board the NASA Terra spacecraft launched in December of 1999 and the other on board the Aqua spacecraft launched in May of 2002, are designed with a wide spectral coverage between 0.4 and 14.3 μm for remote sensing of land, ocean, and atmosphere. Together they have collected more than 10 years of global earth observing data sets. Operational land, ocean, and atmospheric data products are routinely produced and distributed [4]. At present, over 1300 scientific papers involving the MODIS instruments and data products have been published in refereed journals. In spite of MODIS' great successes in earth observations, minor problems with the MODIS instruments do exist. We report in this paper the saturation problems associated with several MODIS channels in the visible and near-IR spectral regions. Scientists and instrument designers should be aware of the problems identified from MODIS design and on-orbit observations so that improved instrument specifications can be made for future earth observing satellite instruments.

2 BACKGROUND

MODIS has a total of 36 channels located within a wide spectral range from 0.4 to 14.3 μm. Among these channels, there are two sub-sets of channels located in the visible and near-IR spectral region between 0.4 and 2.5 μm [5]. One set of channels, Channels 1 – 7, is mainly designed for remote sensing of land and clouds with spatial resolutions (nadir) of 250 m and 500 m. The other set of channels, Channel 8 – 16, with spatial resolution at 1 km, is specifically designed for remote sensing of the darker ocean surfaces. Table 1 summarizes the main characteristics of these two sets of channels. From this table, it is seen that the signal to noise ratios (SNRs) specified for ocean color channels are significantly higher than the corresponding land channels. In addition, the spectral bandwidths for the ocean color channels are narrower than the land channels. Because land is generally brighter than ocean, the

©2007 Society of Photo-Optical Instrumentation Engineers [DOI: 10.1117/1.2712473]
Received 21 Dec 2006; accepted 2 Feb 2007; published 7 Feb 2007 [CCC: 19313195/2007/$25.00]

Downloaded from SPIE Digital Library on 10 Mar 2011 to 128.183.169.235. Terms of Use: http://spiedl.org/terms

spectral radiances and the maximum reflectances specified for land channels are generally larger than those for the corresponding ocean color channels. It should be pointed out that the specified spectral radiances in this table are the radiances expected for typical scenes (L_{typ}). When defining SNRs, the reference signals (or radiances) are the typical scene radiances, not the maximum radiances (L_{max}) above which the channels would saturate.

Table 1. Specifications of two sets of MODIS land and ocean channels in the visible and near-IR spectral regions. Here R_{max} is the maximum equivalent Lambertian reflectance.

Primary use	Channel	Bandwidth (nm)	Spectral radiance (W/m^2-μm-sr)	Signal to noise ratio	R_{max}
Land/Cloud	1	620 – 670	21.8	128	1.49
	2	841 – 876	24.7	201	1.00
	3	459 – 479	35.3	243	1.04
	4	545 – 565	29.0	228	0.93
	5	1230 – 1250	5.4	74	0.51*
	6	1628 – 1652	7.3	275	1.02
	7	2105 – 2155	1.0	110	0.81
Ocean Color	8	405 – 420	44.9	880	0.33
	9	438 – 448	41.9	838	0.23
	10	83 – 493	32.1	802	0.17
	11	526 – 536	27.9	754	0.15
	12	546 – 556	21.0	750	0.12
	13	662 – 672	9.5	910	0.08
	14	673 – 683	8.7	1087	0.07
	15	743 – 753	10.2	586	0.07
	16	862 – 877	6.2	516	0.06

* R_{max} for Channel 5 was changed to 0.80 by the MODIS Project Office in December 1992.

3 SATURATION OF MODIS VISIBLE AND NEAR-IR CHANNELS

Soon after the Terra MODIS data became available for analyses in the spring of 2000, we realized that a number of MODIS channels in the 0.4 to 2.5 μm spectral region could saturate under certain atmospheric and surface conditions. We first reported the saturation problems during the June 2000 MODIS Science Team Meeting. However the saturation problems with MODIS channels have not been generally recognized in the scientific community. Therefore, there is a great need to alert the scientific community and, especially, general users about the saturation problems and to help improve their understanding of existing MODIS data products.

3.1 Ocean color channel saturations

The set of MODIS ocean color channels listed in Table 1 was originally designed for remote sensing of the open ocean water, the so called "case 1" water, under clear to moderate aerosol loading atmospheric conditions. When atmospheric aerosol concentration is high with optical depths greater than about 0.6, or when thin cirrus clouds are present, the atmospheric correction channels, Channels 13, 15, and 16, can saturate because of the specified small saturation radiances and reflectances used for the sensor design and gain setting. Through our further analysis of many sets of MODIS data, we have observed that, even under clear

Downloaded from SPIE Digital Library on 10 Mar 2011 to 128.183.169.235. Terms of Use: http://spiedl.org/terms

atmospheric conditions, other MODIS ocean color channels could saturate over coastal waters, shallow waters with bottom reflections, and open ocean waters coincide with phytoplankton blooming events. Below we show two cases of ocean color channel saturations – one for coastal waters and the other for open ocean waters with phytoplankton bloom.

3.1.1 Bright coastal waters

Figure 1a shows a color image processed from three MODIS land channels (red: Ch. 1; green: Ch. 4; blue: Ch. 3). The Aqua MODIS data were acquired over Florida and Bahamas areas on April 4, 2005 at UTC 1840. Water features southwest to the tip of Florida pan handle are seen obviously from this image. Water features in bluish color in the shallow Bahamas bank areas are also seen clearly. Fig. 1b, 1c, and 1d show the scaled grey images of ocean color channels 10, 11, and 12, respectively. Large portions of the bright water areas seen in Fig. 1a are saturated (completely white) in these figures. The spatial patterns of the saturated areas in Fig. 1b, 1c, and 1d are also somewhat different. Fig. 1d (Channel 12) has the largest areas of saturations. The saturation radiances of the ocean color channels are certainly not sufficiently high to allow the proper observation of the brighter coastal waters.

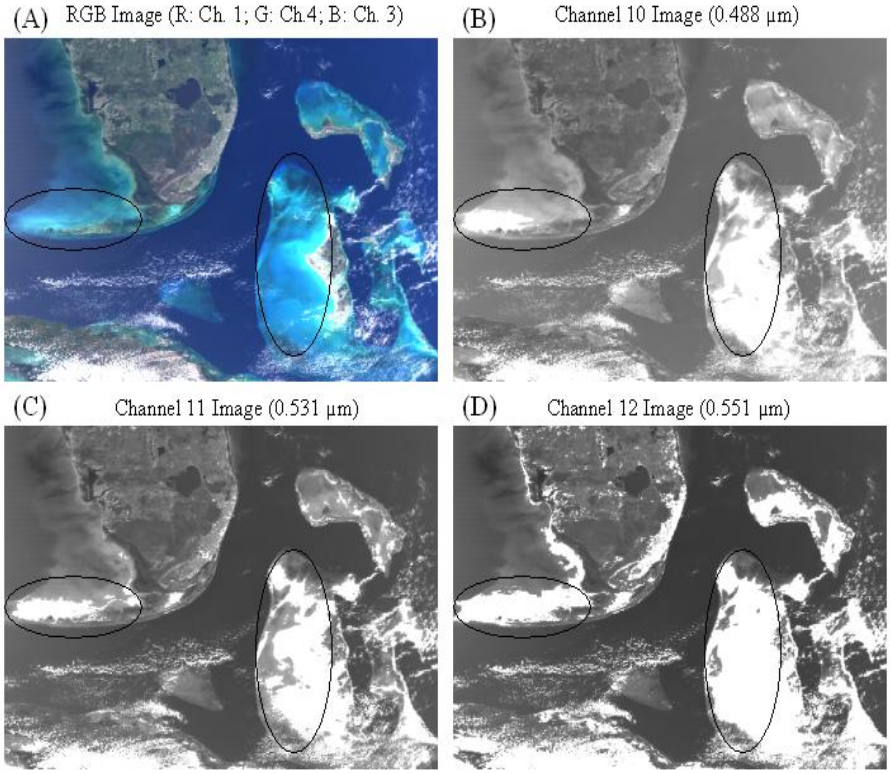

Fig. 1. (a) Color composite image of the MODIS scene acquired on 4 April 2005 over southern Florida and Bahamas areas and processed from three land channels (red: Ch. 1; green: Ch. 4, blue: Ch. 3), (b), (c), and (d) the scaled grey images of the MODIS ocean color channels, 10, 11, and 12, respectively.

Downloaded from SPIE Digital Library on 10 Mar 2011 to 128.183.169.235. Terms of Use: http://spiedl.org/terms

3.1.2 Phytoplankton bloom

Figure 2a shows a color image over the Atlantic Ocean west of France from three MODIS land channels. The Aqua MODIS data were acquired on June 15, 2004 at UTC 1335. The bright features in the water are due to scattering of solar radiation by coccolithophores. Fig. 2b, 2c, and 2d show the scaled grey images of ocean color channels 10, 11, and 12, respectively. Portions of the coccolithophore-covered areas seen in Fig. 2a are saturated in Fig. 2b, 2c, and 2d. Therefore, the saturation radiances for these ocean color channels have significantly hindered proper observations of phytoplankton bloom events over open ocean waters.

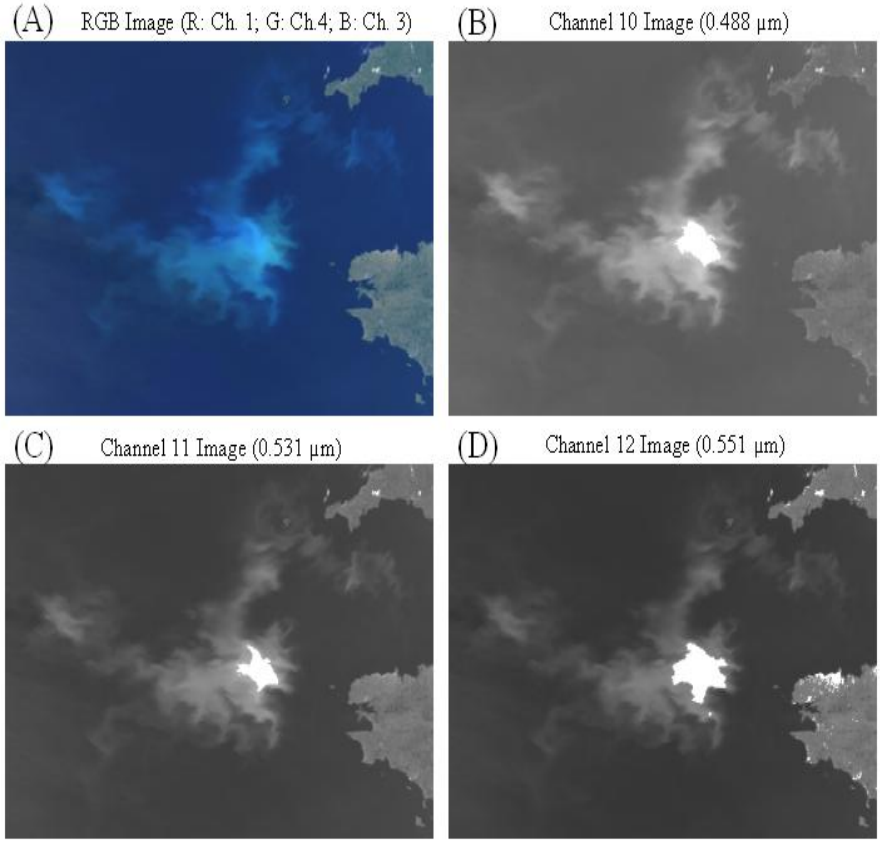

Fig. 2. (a) Color composite image of the MODIS scene acquired over the Atlantic Ocean west of France on 15 June 2004 and processed from three land channels (red: Ch. 1; green: Ch. 4, blue: Ch. 3), (b), (c), and (d) the scaled grey images of the MODIS ocean color channels, 10, 11, and 12, respectively. Notice the saturation of the ocean color channels over the coccolithophore blooming regions.

3.2 Land and atmosphere channel saturations

Channels 1 to 7 listed in Table 1 were designed for remote sensing of land and atmosphere. Channel 5 centered at 1.24 μm was originally geared for remote sensing of vegetation liquid water. The maximum reflectance was specified at 0.51 during the early definition phase of the MODIS instrument [5]. Water clouds are typically brighter than land surfaces. The 1.24-μm water cloud reflectances can be greater than 0.51. In order to seek a compromise between land

Downloaded from SPIE Digital Library on 10 Mar 2011 to 128.183.169.235. Terms of Use: http://spiedl.org/terms

and cloud applications for Channel 5, a suggestion was made by Bo-Cai Gao to raise the maximum reflectance to 0.8 and accepted by the NASA MODIS Project Office in December 1992. Although the modified channel does not saturate over many clouds, it still saturates over deep convective clouds in tropical regions.

Figure 3a shows a Terra MODIS Channel 1 image acquired over a tropical region in Central America on April 9, 2000 at UTC 1625. Fig. 3b shows the corresponding Channel 5 image. Over portions of the bright clouds in this image, Channel 5 is saturated (bright white) while Channel 1 is not. This is because Channel 5 has a maximum reflectance of 0.8, while Channel 1 has a much greater maximum reflectance of 1.49 (see Table 1).

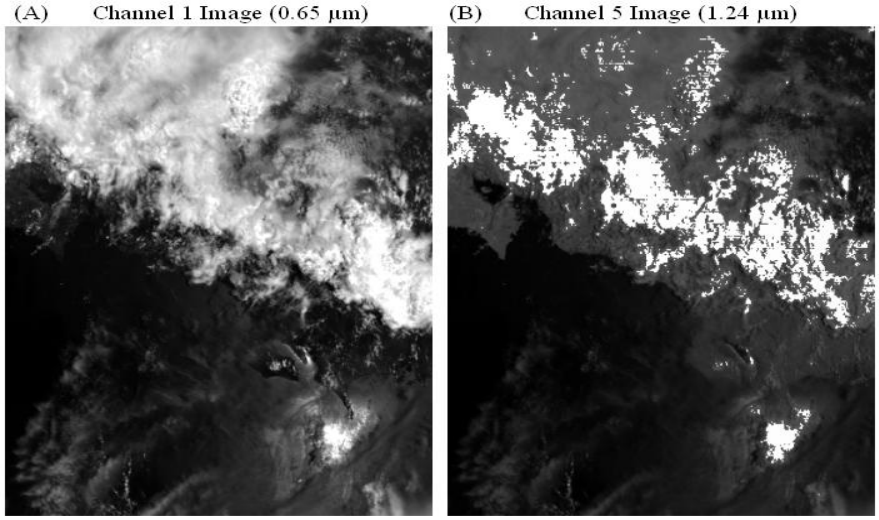

Fig. 3. (a) Terra MODIS Channel 1 image acquired over a tropical region in Central America on April 9, 2000, and (b) the Channel 5 image over the same area.

We have made a comprehensive study of Terra MODIS data in the tropical region in a latitude range between –30 and +30 degrees for the time period from April 1 to September 30, 2000. We selected a total of 5187 daytime MODIS granules with the middle point geolocations located within the latitudes of +/-20 degrees to guarantee the whole granule pixels are between the latitudes of +/-30 degrees. Each granule covers a surface area of approximately 2800 by 2000 km. Table 2 gives the statistics of the saturated pixels for Channels 1 – 7 in the selected MODIS data set. The percentages of saturated pixels for Channels 2, 5, and 7 averaged over all the selected granules are 1.0767, 2.7535, and 0.1767, respectively. These numbers do not seem to be large. However, the maximum percentages of saturated pixels of the three channels for certain individual granules are 12.244, 31.796, and 16.7950, respectively. Quite significant amounts of pixels are saturated over these granules, mainly due to reflection of solar radiation by bright clouds (see Fig. 3b). Table 2 also indicates that channels 1, 3, 4, and 6 are less likely to saturate over tropical clouds.

Table 2. Statistics of saturated pixels of Channels 1 to 7 for Terra MODIS data located within a latitude range between –30 and +30 degrees for a time period from April 1 to September 30, 2000.

Channel #	1	2	3	4	5	6	7
% of saturated pixels (Average over all granules)	0.0004	1.0767	0.3053	0.1665	2.7535	0.0001	0.1767

Downloaded from SPIE Digital Library on 10 Mar 2011 to 128.183.169.235. Terms of Use: http://spiedl.org/terms

% of saturated pixels (Maximum of one granule)	0.4930	12.244	6.1890	4.1360	31.796	0.4430	16.795

4 DISCUSSIONS

The specifications of the MODIS instrument have greatly influenced the specifications of other satellite instruments, such as the Japanese Global Imager (GLI) onboard the Advanced Earth Observing Satellite II, and the future US Visible Infrared Imaging Radiometer Suite (VIIRS) to be onboard the National Polar-orbiting Operational Environmental Satellite System (NPOESS) [6]. The designers of the GLI instrument followed very closely with the MODIS channel specifications but performed additional radiative transfer modeling studies [7]. A few GLI channels were basically not suitable for remote sensing of ocean color because of saturation problems.

In view of the obvious saturation effects of MODIS ocean color channels, such as those illustrated in Fig. 1 and Fig. 2, we would like to suggest that the saturation radiances of future satellite ocean color channels should be increased in comparison with the current MODIS channels (see Table 1). Based on our experience with analysis of MODIS data, we would like to suggest that an across board increase in saturation radiances for channels between 480 and 900 nm (MODIS Channels 10 to 16) by approximately 20% should be considered when designing the future ocean color satellite sensors. Of course, scientists and engineers should also make detailed sensitivity studies using existing satellite data and radiative transfer models before finalizing their channel specifications.

It is understood that an increase of saturation radiance, or maximum radiance (L_{max}), of a channel will lead to a decrease of signal resolution and an increase of digitization error. One has to make sure that the resolution-limited (due to digitization) signal-to-noise ratio (SNR) will continue to be larger than the specified SNR at typical scene spectral radiance (L_{typ}) shown in Table 1. For MODIS ocean channels 10 to 16, the ratios of specified (design) maximum radiances to specified typical radiances (L_{max}/L_{typ}) and the projected digital number (dn) at L_{typ} with a 20% increase of L_{max} for a 12-bit sensor (3800 counts out of 4096 are used after consideration of the dark counts or the signal offsets) are shown in Table 3. Also shown in this table is the resolution-limited SNR estimated using a digitization error of 0.5 digital count. It is obvious to see that the new resolutions with proposed increase of saturation radiances are sufficiently adequate to satisfy the original specified SNRs. Analysis of sensor on-orbit SNR performance [8] also indicates that there are enough resolution margins for a 20% increase of saturation radiances for MODIS bands 10-16.

Table 3. Comparison of specified sensor SNR and resolution-limited SNR for MODIS channels 10-16 with a 20% increase of saturation radiance (L_{max}) and a digitization error of 0.5 digital count.

Channel	Specified Sensor SNR	L_{max}/L_{typ}	Digital Number at L_{typ}	Resolution-Limited SNR
10	802	3.1	1209	1932
11	754	2.9	1293	2069
12	750	3.0	1247	1995
13	910	3.4	1128	1805
14	1087	3.6	1066	1706
15	586	2.5	1491	2385
16	516	2.6	1473	2356

Downloaded from SPIE Digital Library on 10 Mar 2011 to 128.183.169.235. Terms of Use: http://spiedl.org/terms

5 SUMMARY

The MODIS ocean color channels were originally designed for remote sensing of the "case 1" waters. We have reported in this paper that these channels can saturate over the brighter coastal waters, shallow waters with bottom reflections, and open waters when phytoplankton blooming occurs. We have also reported that some MODIS land channels in the visible and near-IR spectral region can saturate over bright clouds in the tropical region. Scientists and instrument designers should be aware of the MODIS saturation problems so that improved instrument specifications can be made for future earth observing satellite instruments.

Acknowledgments

The authors would like to thank K.-F. Chiang of MODIS Characterization Support Team with Science Systems and Applications, Inc., for help during data analysis. This research was supported by the NASA Goddard Space Flight Center under the MODIS Project and the U.S. Office of Naval Research.

References

[1] V. V. Salomonson, W. L. Barnes, P. W. Maymon, H. E. Montgomery, and H. Ostrow, "MODIS: Advanced facility instrument for studies of the earth as a system," *IEEE Trans. Geosci. Remote Sens.,* **27**, 145-153 (1989) [doi:10.1109/36.20292].

[2] W. E. Esaias, M. R. Abbott, I. Barton, O. B. Brown, J. W. Campbell, K. L. Carder, D. K. Clark, R. H. Evans, F. E. Hoge, H. R. Gordon, W. M. Balch, R. Letelier, and P. J. Minnett, "An overview of MODIS capabilities for ocean science observations," *IEEE Trans. Geosci. Remote Sens,* **16***,* 1250-1265 (1998) [doi:10.1109/36.701076].

[3] M. D. King, W. P. Menzel, Y. J. Kaufman, D. Tanre, B.-C. Gao, S. Platnick, S. A. Ackerman, L. A. Remer, R. Pincus, and P. A. Hubanks, "Cloud and aerosol properties, precipitable water, and profiles of temperature and humidity from MODIS," *IEEE Trans. Geosci. Remote Sens*., 41, 442-458 (2003) [doi:10.1109/TGRS.2002.808226].

[4] V. V. Salomonson, W.L. Barnes, X. Xiong, S. Kempler, and E. Masuoka, "An Overview of the Earth Observing System MODIS Instrument and Associated Data Systems Performance", *Proc. IGARSS'02,* **2**, 1174 – 1176 (2002).

[5] M. D. King, Y. J. Kaufman, W. P. Menzel, and D. Tanre, "Remote sensing of cloud, aerosol and water vapor properties from the Moderate Resolution Imaging Spectrometer (MODIS)," *IEEE Trans. Geosci. Remote Sens.,* **30**, 2-27 (1992) [doi:10.1109/36.114212].

[6] C. F. Schueler, J. E. Clement, S. W. Miler, P. M. Kealy, P. E. Ardanuy, S. A. Cota, F. J. De Luccia, J. M. Haas, S. A. Mango, K. S. Speidel, and H. Swenson, "NPOESS VIIRS: Next-generation polar-orbiting atmospheric imager," *Proc. SPIE. Int. Soc. Opt. Eng.*, **4891**, 50 (2003) [doi:10.1117/12.467564].

[7] T. Y. Nakajima, T. Nakajima, M. Nakajima, H. Fukushima, M. Kuji, A. Uchiyama, and M. Kishino, "Optimization of the advanced earth observing satellite II global imager channels by use of radiative transfer calculations," *Applied Optics*, **37**, 3149-3163 (1998).

[8] Xiong X, J. Sun, W. Barnes, V. Salomonson, J. Esposito, H. Erives, and B. Guenther, "Multi-year On-orbit Calibration and Performance of Terra MODIS Reflective Solar Bands", accepted for *IEEE Tran. Geosci. Remote Sens.*, 2007.

Downloaded from SPIE Digital Library on 10 Mar 2011 to 128.183.169.235. Terms of Use: http://spiedl.org/terms